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Research Article

Empirical Relationships among Pedestrian Flow Characteristics in an Indoor Facility

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Abstract: Pedestrian flow characteristics are site and region specific. For developing a safe evacuation system for indoor facilities, pedestrian characteristics on such facilities should be well understood. In this study, the findings of a study of pedestrian flow characteristics for level walkways and stairways inside a hall room type facility are described. The empirical relationships between different pedestrian characteristics are presented mathematically as well as graphically. In addition, the free-flow speeds of pedestrians for level walkways and stairways are observed, which is necessary to assess the pedestrian flow characteristics at high congestion. The comparison of the findings of current study with that of other previous studies on outdoor and different types of indoor facilities indicates the significance of this study. The relationships that have been established in this study could be used as guidelines for the development of evacuation models for hall room type facilities.

Keywords: Density, free flow, level walkway, pedestrian module, stairway, walking speed

INTRODUCTION

A facility or building may need to be evacuated in many hazardous situations like fire, bomb blast, earthquakes, etc. The life safety code handbook by National Fire Protection Association (NFPA) (Cote and Harrington, 2006) has been formulated to make such evacuations easy from buildings. To follow such codes for evacuation, predetermined evacuation maps are placarded at noticeable places of the buildings. In emergency, the occupants need to follow these maps by themselves with only some assistance of some assigned personnel. Despite these directions, there is an inclination in people to go after the mass which could increase congestion in passageways and stairwells. Thus, for the safe evacuation from any facility it is important to understand the basic pedestrian characteristics and their relationships both for emergency and non-emergency situations. This information may be inputted to the standard codes for evacuating particular occupants. Since it is almost impossible to collect real data on pedestrian flow characteristics during emergency, we need to infer the emergency situation based on the data collected on non-emergency situations.

According to May (1990), pedestrian flow characteristic is divided into two levels as microscopic level and macroscopic level. Microscopic level involves individual traffic characteristics such as individual speed and individual interaction (Teknomo, 2002). Macroscopic study gives on the whole an averaged view of pedestrian flow scenario where the main concern is the space allocation for pedestrians in the facility. Fruin (1971) is one of the pioneers who suggested the macroscopic concept for pedestrian flow which was later on adopted by Transportation Research Board (1985). The different methods of data-collection for macroscopic study were recommended by the Institute of Transportation Engineers (1994).

Numerous researches have been done on the pedestrian characteristics for sidewalks, stairways and crosswalks of different countries. These studies show that pedestrian characteristics may vary because of age, gender and locations. Tanaboriboon *et al*. (1986) studied the characteristics of pedestrians in different sidewalks of Singapore and found a slower walking speed compared to Western countries. Tanaboriboon and Guyano (1991) also pointed out that walking speeds are different for pedestrians of Asian and Western countries. Morrall *et al*. (1991) presented an extensive review of Asian pedestrian characteristics. Sarkar and Janardan (2001) studied the pedestrian speed density relationships for an inter-modal transfer terminal in India and Laxman *et al*. (2010) also studied pedestrian characteristics for a different city of India in mixed traffic condition and showed that the characteristics of the location and pedestrian themselves have their effect on the pedestrian flow characteristics.

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Rahman *et al*. (2012) studied the effect of different factors and their interactions on free flow walking speed in Bangladesh and found a significant effect of personal and location factors on pedestrian walking speed. Lam and Cheung (2000) found a higher free-flow and mean walking speed for outdoor walkways compared to indoor walkways. A larger speed of pedestrian on downstairs than on upstairs was observed by Liu *et al*. (2008).

Compared to empirical studies on pedestrian flow characteristics based on outdoor facilities, only a limited number of researches have been done based on indoor facilities. For the purpose of safe evacuation from any facility, pedestrian characteristics for indoor facilities should be well understood. The pedestrians' walking speed is a major concern in the study of the evacuation of facilities, as it is linked directly with the capability of a walkway to keep up a preferred flow of pedestrians along its length.

According to Fruin (1970) pedestrian mean speed under the free flow condition is necessary to assess the pedestrian characteristics at high density of traffic. Polus *et al*. (1983) found that no significant change of pedestrian preferred speed occurred for densities of less than or equal to 0.6 ped/m^2. However Ando *et al.* (1988) noted that the free flow walking condition is applicable up to the density of 0.8 ped/m^2 for horizontal movement. But these studies were conducted for outdoor walkways and railway station, respectively. Liu *et al*. (2008) showed that in upward stairs the free flow speed is maintained for densities less than or equal to 0.5 ped/m^2, but in downward stairs this value is less than or equal to 0.4 ped/m^2.

Previous related studies on pedestrian characteristics showed that free flow features of pedestrians depend on facility type and on regions and are not common (Rahman *et al*., 2013a). To perform an efficient evacuation from a facility, it is required to conduct further study on pedestrian free flow characteristics inside such facility. To our knowledge only a limited number of researches have been done to find the free flow walking speed of pedestrians inside a hall room.

For this study, walking speeds for varying densities were monitored in a hall room to examine the relationships between them for level walkways and stairways. The pedestrian characteristics at the Dewan Tuanku Syed Putra (DTSP) hall room of University Sains Malaysia were considered for this study. The findings of this study will be a significant contribution to an active field of research and a resource for those developing evacuation models in practice. The rest of the paper is arranged in the following manner. An outline of data collection surveys is presented, followed by a discussion of the survey results on pedestrian walking speed, density and flow. Some speed-density-flow models have been developed for level walkways, upward stairways and downward stairways. Finally, conclusions are drawn and recommendation is given for further study.

MATERIALS AND METHODS

Data collection procedure: Data collection surveys were undertaken during the convocation 2011 using photographic procedure. Each day there were two sessions and the data for level walkways were collected at the end of each session when the graduates and their guests were going out from the DTSP hall room. Three different walkways inside the hall room and two different stairways were selected for data collection. Three video cameras were placed on three different fixed positions on the first floor by tripod to record the pedestrian movements on the selected test stretches inside the hall room. Two cameras were placed in front of two stairs and data were collected when people entered the hall room at the beginning of each session and when people came out from hall room at the end of each session. The width of the walkways and stairways were fixed throughout the observed length for a set of data. The pedestrian flows were unidirectional and available for varying densities (that is, from low-density to high-density). The recording was done in such a way that pedestrian natural movements were not affected by the presence of recording instruments and also not affected by anything outside the test stretches. The physical characteristics of the observation sites for level walkways and stairways are presented in Table 1 and 2, respectively.

Data extraction: The recorded video files of the pedestrian movements were then played using Adobe Premiere Pro software and the following steps were used for data extraction (Al-Azzawi and Raeside, 2007):

- A pedestrian about to enter the system was randomly selected and was tracked through the observation site.
- His or her entry and exit times in and out of the site were recorded. Pedestrian traverse time was

Table 1: Physical characteristics of observed level walkways

Level walkway	Width (in m)	Length (in m)
Level walkway 1	2.0	10.1
Level walkway 2	1.2	18.0
Level walkway 3	1.2	9.0

Table 2: Physical characteristics of observed stairways

Stairways	Width (in m)	Length (in m)	Riser height (in cm)	Tread width (in cm)	Angle (in deg)
Stairway 1	0.93	5.25	13.60	28	35.6
Stairway 2	0.91	5.18	13.42	28	25.9

Table 3: Pedestrian free flow walking speeds

Observation sites		Avg. free flow speed (m/sec)	S.D. (m/sec)	Range Min. (m/sec)	Range Max. (m/sec)
Level walkways		1.41	0.28	1.05	1.86
	Male	1.42	0.29	1.06	1.86
	Female	1.39	0.30	1.05	1.80
Upward stairways		0.51	0.15	0.28	1.30
	Male	0.54	0.16	0.29	1.30
	Female	0.49	0.14	0.28	1.30
Downward stairways		0.54	0.21	0.40	1.05
	Male	0.69	0.27	0.44	1.05
	Female	0.44	0.05	0.40	0.53

Min.: Minimum; Max.: Maximum; S.D.: Standard deviation; Avg.: Average

computed by subtracting the entrance time into the site from the exit time.

- Walking speed was then derived by dividing the length of the observation site by the traverse time.
- The video file was rewind back to when the selected pedestrian was approximately in the middle of the observation site, then the video was paused and the total number of pedestrians in the site with the selected person was counted. Density was then computed by dividing the counted number of pedestrians by the area of the observation site.
- The gender of the selected pedestrian was also recorded.
- The process was repeated until the video file was completely extracted.

In total, 115 pedestrians for level walkways, 235 pedestrians for upward stairways and 209 pedestrians for downward stairways were observed for data extraction.

RESULTS AND DISCUSSION

Free flow walking speeds: Free flow walking speed reflects the desired speed of a pedestrian that she or he can maintain without getting obstructed by other people in front of her or him. In this study, the pedestrians who seemed to maintain their desired walking speeds through the length of the observation site without any conflict with other pedestrian were considered for calculating the free flow walking speeds. Table 3 presents the average, standard deviation and range of pedestrian free flow walking speeds for level walkways and stairways. The walking speeds for male and female pedestrians are also presented.

The overall free flow walking speed for level walkways was observed as 1.41 m/sec. This observed speed was higher compared to the study conducted by Lam *et al*. (1995) inside a railway station (0.83 m/sec). The difference in speeds may be explained as the speed also depends on the walking purpose of the pedestrians. It seems that there is a higher speed for egress from a hall room than from a railway station. It was also observed that free flow walking speeds were slightly higher for male than female, 1.42 versus 1.39 m/sec, respectively.

Table 4: Pedestrian flow rates

Observation sites	Observed flow rates Min. (ped/m/sec)	Max. (ped/m/sec)
Level walkways	0.27	1.87
Upward stairways	0.06	0.73
Downward stairways	0.08	0.88

Min.: Minimum; Max.: Maximum

The speeds on both upward and downward stairways (0.51 and 0.54 m/sec) were typical for other Asian studies such as Bangkok (Tanaboriboon and Guyano, 1991) and Hong Kong (Lam *et al*., 1995). The walking speed on level walkways differed significantly from that of both upward and downward stairways. These results support the findings of others researches (Lam *et al*., 1995; Morrall *et al*., 1991; Rahman *et al*., 2012; Tanaboriboon and Guyano, 1991).

Walking speeds on stairways were higher downward than upward, which also supported the findings of previous studies (Lam *et al*., 1995; Liu *et al*., 2008; Tanaboriboon and Guyano, 1991). In both upward and downward stairways male were observed to walk faster than female, but the difference was statistically insignificant. This may happened because movements on stairways were more restricted compared to level walkways, which decreased the difference of walking speeds between male and female pedestrians.

Observed flow rates: Table 4 gives the minimum and maximum flow rates by different observation sites. The maximum flow rate observed for level walkways was 1.87 ped/m/sec, which was greater than the flow rates of indoor walkways reported by Lam *et al*. (1995). This may be because of the higher egress speed of pedestrians inside a hall room than from a railway station.

Speed-density-flow models:

Level walkways: The relationship between pedestrian speed and density for level walkways is presented in Fig. 1 through a scatter diagram. The best fitted line to the observed data is an exponential line with R^2 equal to 0.87. The fitted equation is as follows:

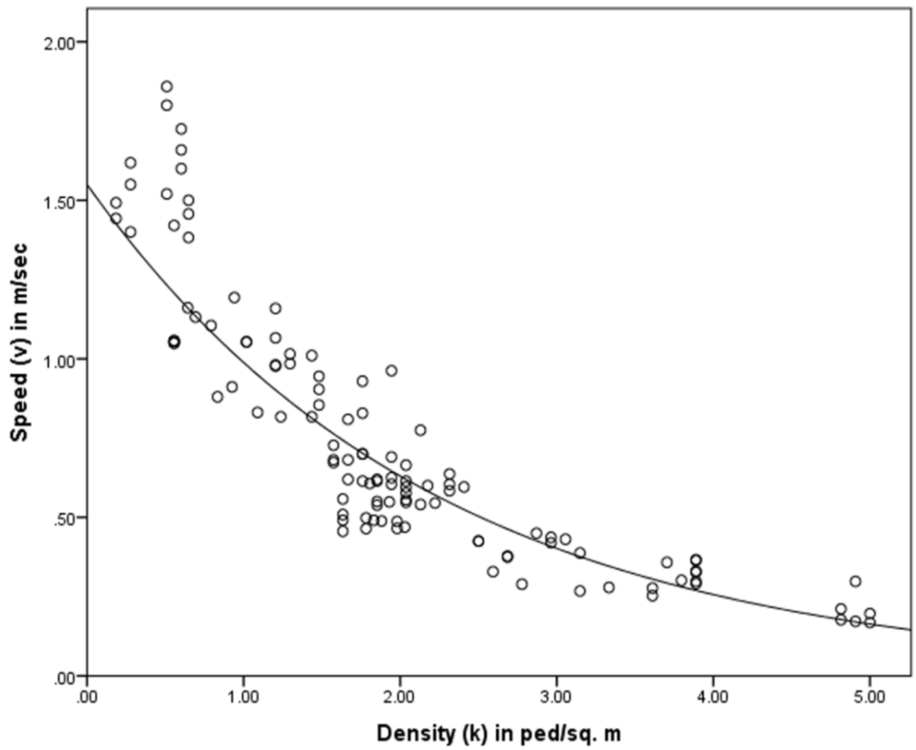

Fig. 1: Speed-density relationship for level walkways

Table 5: A comparison between observed and estimated walking speeds for level walkways

Mean difference	S.D.	95% C.I. of the differences Lower	Upper	Calculated t-value	Degrees of freedom	p-value
0.02358	0.16788	-0.00743	0.05460	1.507	114	0.135

S.D.: Standard deviation

$$v = 1.55e^{-(0.45k)} \quad (1)$$

where,
v = Walking speed in meters per second
k = Density in pedestrians per square meter

In this study, putting k = 0 into the Eq. (1) gives an average free flow walking speed of 1.55 m/sec, which is not equal to the observed free flow walking speed (1.41 m/sec). Sarkar and Janardhan (2001) and Laxman *et al*. (2010) computed the average free flow walking speed by putting density equal to zero to the speed-density equation. But Lam *et al*. (1995) and Rahman *et al*. (2013a) showed that this method of calculating the average free flow walking speed was not accurate. This is because the density can never be zero with the existence of a lone pedestrian.

For nonlinear curves, R^2 (Explained Sum of Squares/Total Sum Squares) may not be a meaningful descriptive statistics because the residuals do not necessarily sum to zero, also the sum of Explained Sum of Squares (ESS) and Residual Sum of Squares (RSS) does not necessarily equal to Total Sum of Squares (TSS) (Gujarati, 2003). Hence, a paired t-test was performed between estimated and observed walking speeds to see whether the fitted line described the observed data or not (Rahman *et al*., 2013b). The result did not show any significant difference between the observed and estimated speed (Table 5). This means that the fitted equation describes the observed data very well.

The pattern of the fitted speed-density equation also agrees with Underwood model (Underwood, 1960) and the exponential walking speed model developed by Yuhaski and Smith (1989). Tregenza (1976) showed that pedestrian flow stopped at a density of 5 ped/m^2. However, according to Yuhaski and Smith (1989), there may still be some forward movement when the number of pedestrian reaches the capacity of a corridor. The fitted equation agreed with this feature as well.

Equation (2) presents the relationship between pedestrian flow and pedestrian density inside the DTSP hall room, while Eq. (3) presents the relationship between pedestrian flow and walking speed:

$$q = 1.55\,k.e^{-(0.45k)} \quad (2)$$

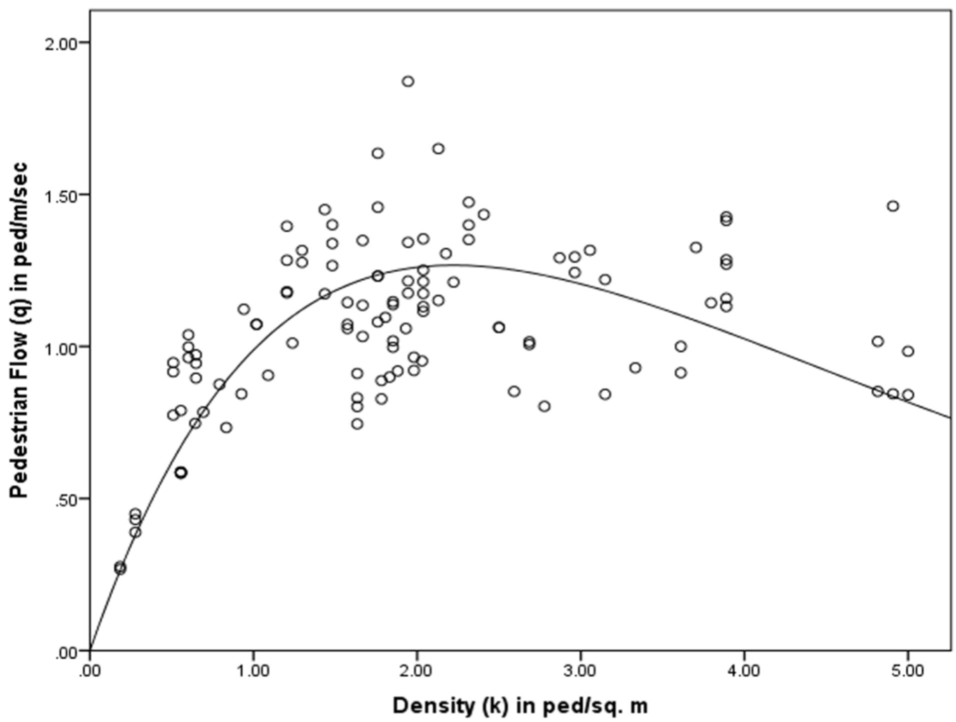

Fig. 2: Flow-density relationship for level walkways

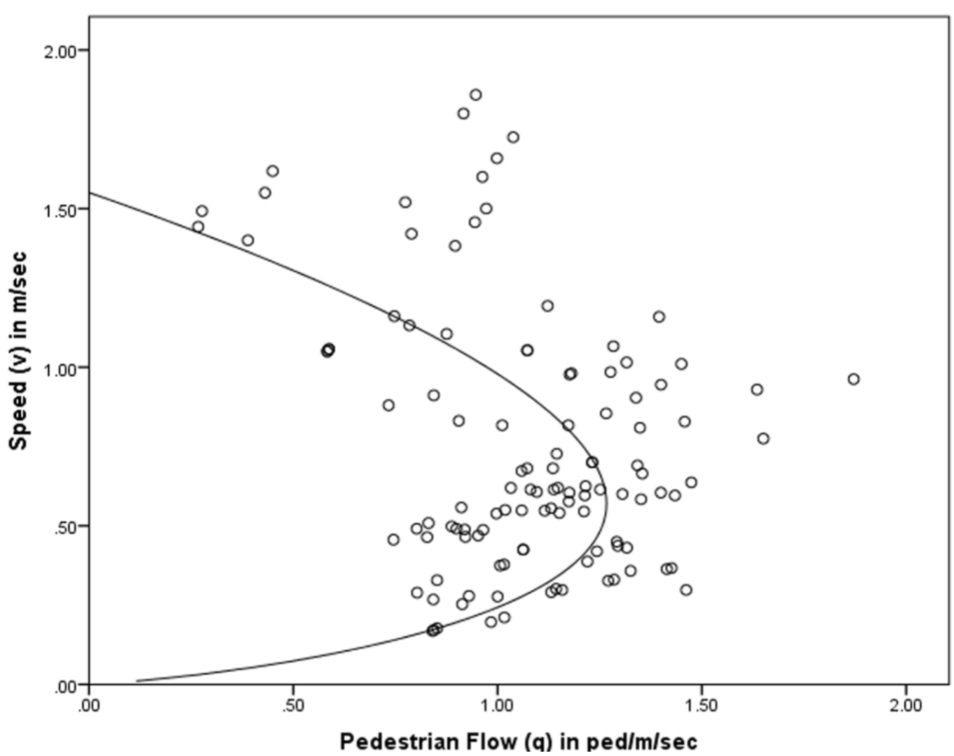

Fig. 3: Speed-flow relationship for level walkways

$$q = v(0.9739 - 2.22\ln(v)) \quad (3)$$

where, q is pedestrian flow in pedestrian per meter per second.

The scatter diagrams of flow-density and speed-flow relationships along with the fitted curves are presented in Fig. 2 and 3, respectively. For both cases, the relationships are parabolic.

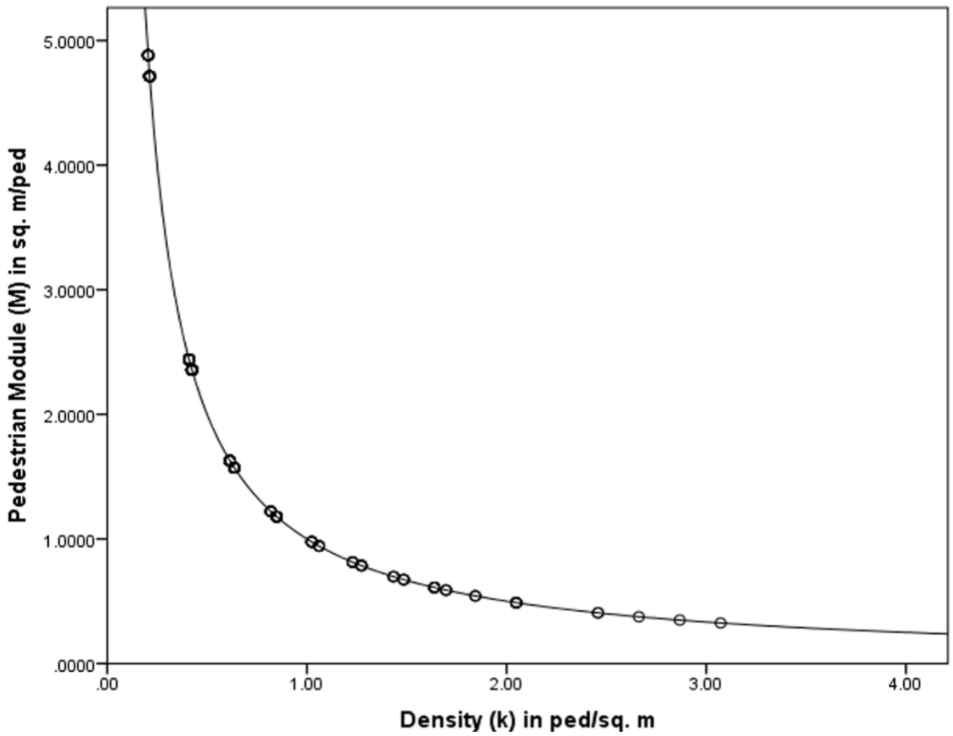

Fig. 4: Pedestrian module-density relationships for level walkways

The flow-density relationship in Fig. 2 shows that the pedestrian flow increases up to a limit as the density increases and then it starts to decrease for further increase in density. The relationship between pedestrian speed and flow may be considered in two phases as Fig. 3 shows two values of speed corresponding to each value of flow.

At the upper phase, there is a negative relationship between speed and flow and there would not be any downstream blockage to affect the forward movements. Yet, because of the physical interactions among the pedestrians the speed may decrease. At the lower phase, after the pedestrian flow reaches the maximum value, speed and flow have a positive relationship. For further increase in flow there will be a downstream blockage that will decrease the flow rate. Also, the increased physical interaction among the pedestrians decreases the speed.

Fruin (1970) recommended the use of pedestrian module, which measures the available space for a pedestrian, to envisage the relative ease experienced by a pedestrian. Figure 4 shows how the pedestrian area occupancy decreases with the increase in density inside DTSP hall room. The fitted relationship between pedestrian flow and pedestrian module shows an inverse parabolic relationship, which is approximated by Eq. (4):

$$q = \frac{1.55}{M}.e^{-\frac{0.45}{M}} \tag{4}$$

where, M is the pedestrian module in square meter per pedestrian.

Figure 5 presents the scatter diagram of flow-pedestrian module relationship in conjunction with fitted curve for level walkways inside the hall room. Pedestrian flow is observed to increase to its maximum for an increase in pedestrian module up to the value of 0.45 m^2/ped and then it starts to decrease for further increase in pedestrian module. A similar pattern for pedestrian flow and pedestrian module relationship was also observed for outdoor walking facilities (Rahman *et al*., 2013a).

Upward stairways: Movement on upward stairs is more controlled than walking on level walkways because of the restrictions caused by the stairs steps and also the pedestrians need to move against the gravity. The scatter diagram of speed-density relationship for upward stairways is presented in Fig. 6. The fitted curve to the data is an exponential curve, which is expressed through Eq. (5):

$$v = 0.558e^{-(0.322k)} \tag{5}$$

A paired t-test between the estimated and observed value of speed is performed to check the adequacy of the fitted line. Table 6 shows that there is no significant difference between the observed and estimated pedestrian speeds for upward stairways.

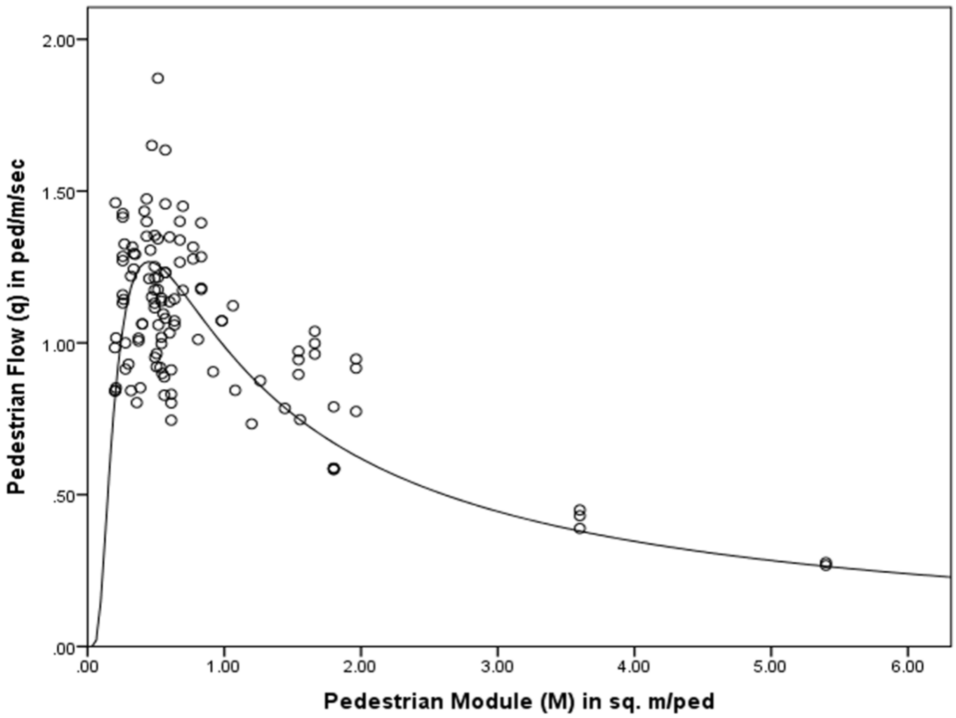

Fig. 5: Flow-pedestrian module relationship for level walkways

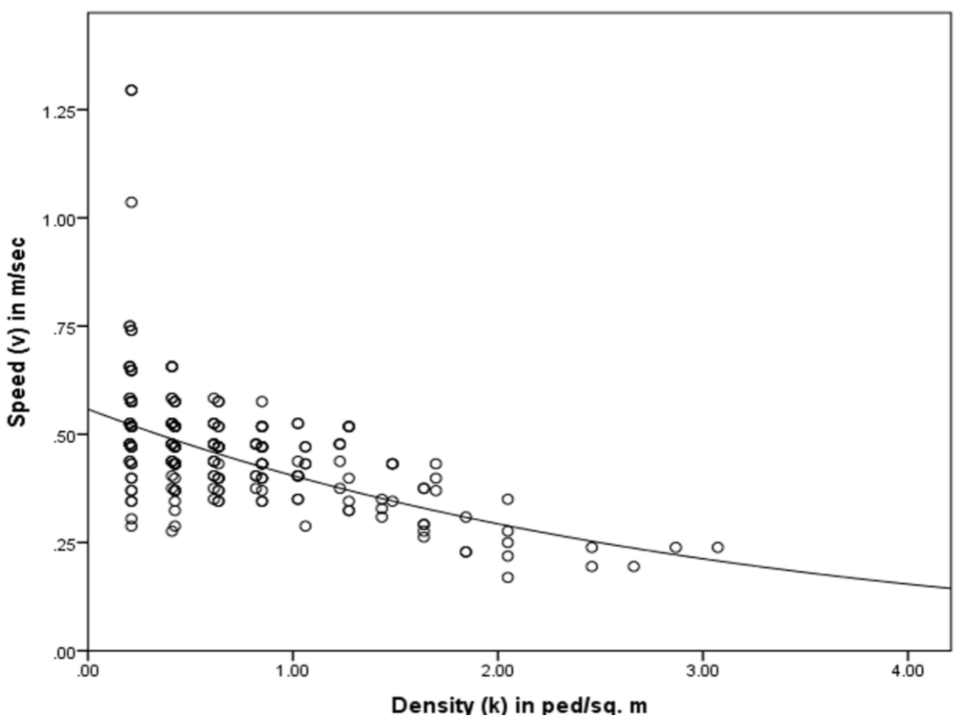

Fig. 6: Speed-density relationship for upward stairways

Table 6: A comparison between observed and estimated speeds for upward stairways

Mean difference	S.D.	95% C.I. of the differences Lower	Upper	Calculated t-value	Degrees of freedom	p-value
0.01068	0.11383	-0.00395	0.02531	1.438	234	0.152

S.D.: Standard deviation

The flow-density and speed-flow relationship for upward stairways is presented in Fig. 7 and 8, respectively. The figures show associated parabolic relationships. Equation (6) and (7) are the corresponding fitted equations:

$$q = 0.558k.e^{-(0.322k)} \qquad (6)$$

$$q = v(-1.8118 - 3.1056 \ln(v)) \qquad (7)$$

The flow-pedestrian module relationship for upward stairways also shows a similar inverse parabolic pattern as level walkway, which is presented in Fig. 9 along with the fitted line based on Eq. (8). It is observed that for maximum flow on upward

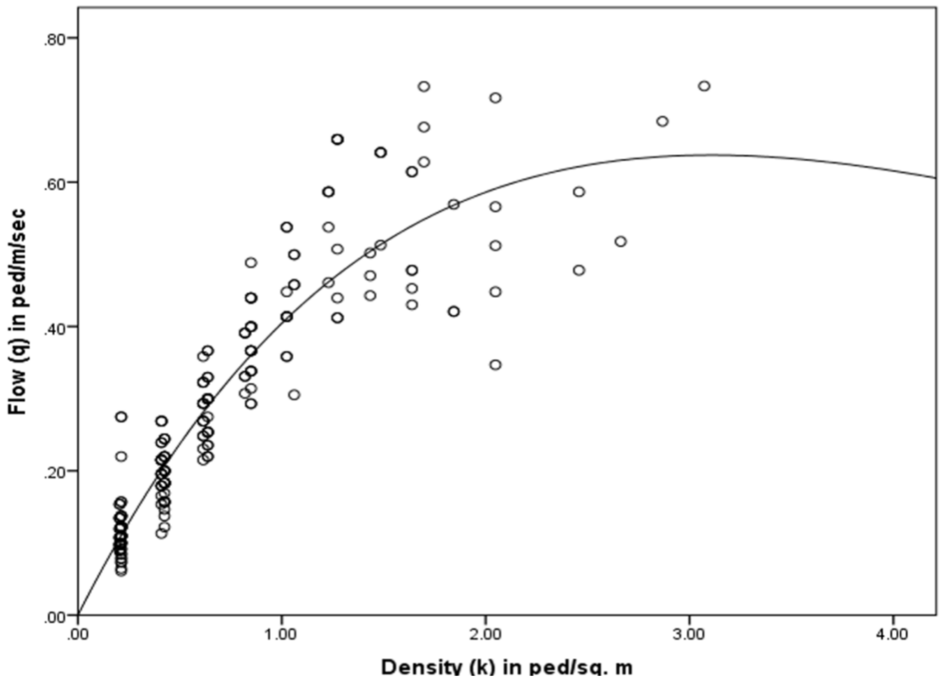

Fig. 7: Flow-density relationship for upward stairways

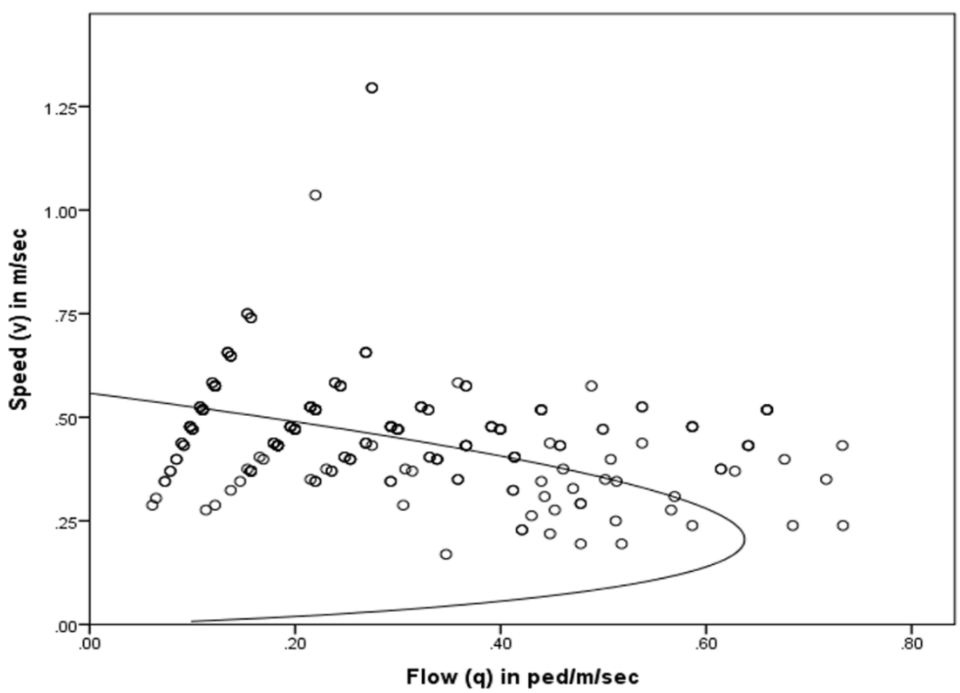

Fig. 8: Speed-flow relationship for upward stairways

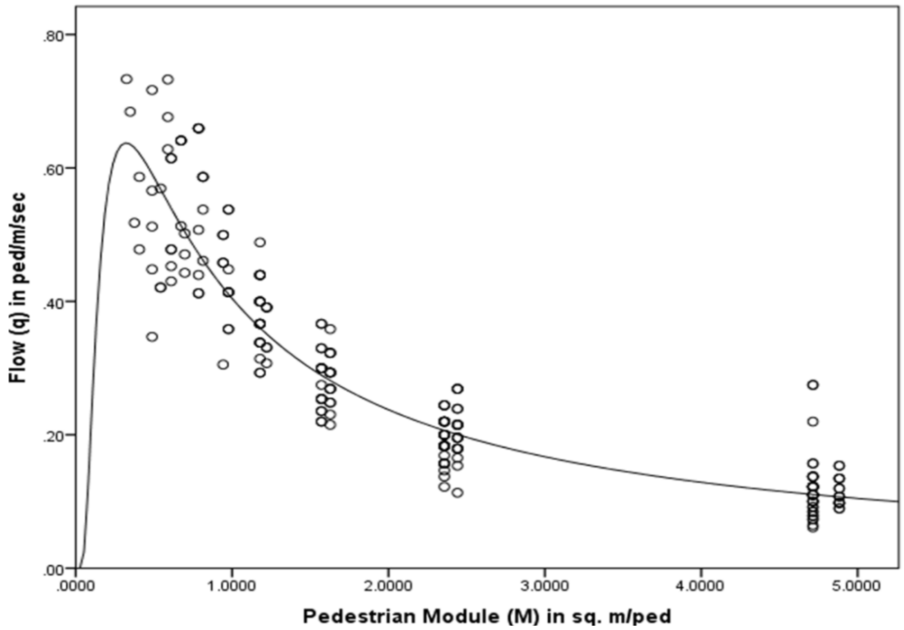

Fig. 9: Flow-pedestrian module relationship for upward stairways

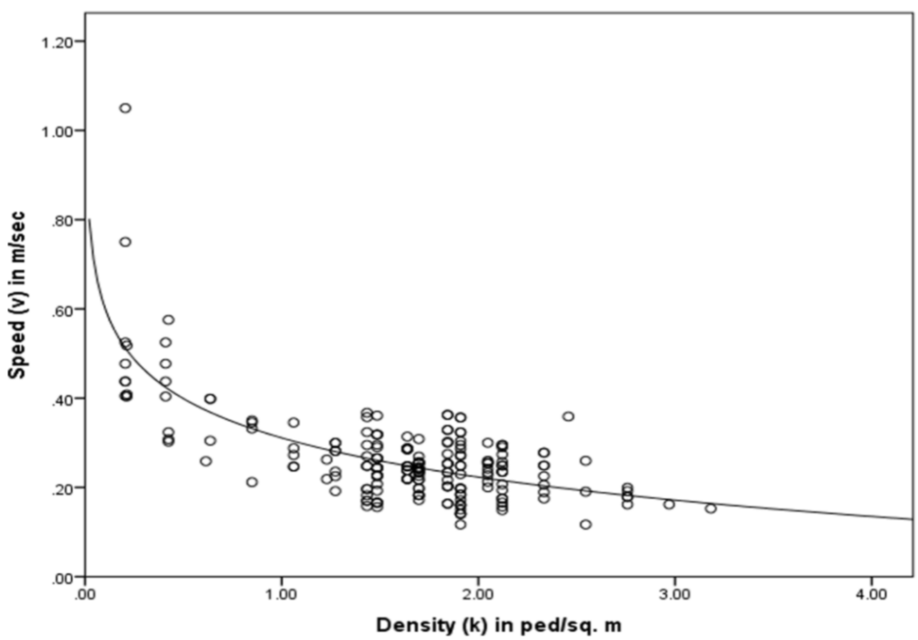

Fig. 10: Speed-density relationship for downward stairways

stairways, an occupancy area of 0.32 m^2 is required for a pedestrian:

$$q = \frac{0.558}{M} e^{-\left(\frac{0.322}{M}\right)} \tag{8}$$

Downward stairways: Since pedestrians need to control gravity safely in downward movements through stairs, the movement is more structured and restricted than walking on level walkways (ITE Technical Council Committee 5-R, 1976). Figure 10 presents the speed-density relationship and the fitted curve for downward stairways. The figure shows that the best fitted line is logarithmic which is given by Eq. (9):

$$v = 0.311 - 0.127 \ln(k) \tag{9}$$

Also the paired t-test between the estimated and observed values of speed suggest that the observed values of speed are well-described by the estimated line (Table 7).

Table 7: A comparison between observed and estimated speeds for downward stairways

Mean difference	S.D.	95% C.I. of the differences Lower	Upper	Calculated t-value	Degrees of freedom	p-value
0.00009	0.07046	-0.00952	0.00970	0.019	208	0.985

S.D.: Standard deviation

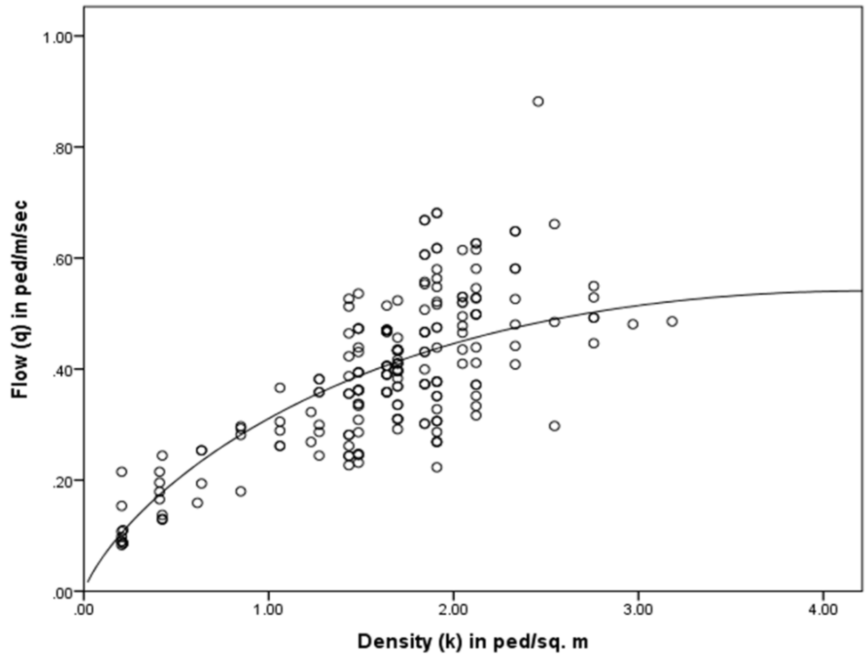

Fig. 11: Flow-density relationship for downward stairways

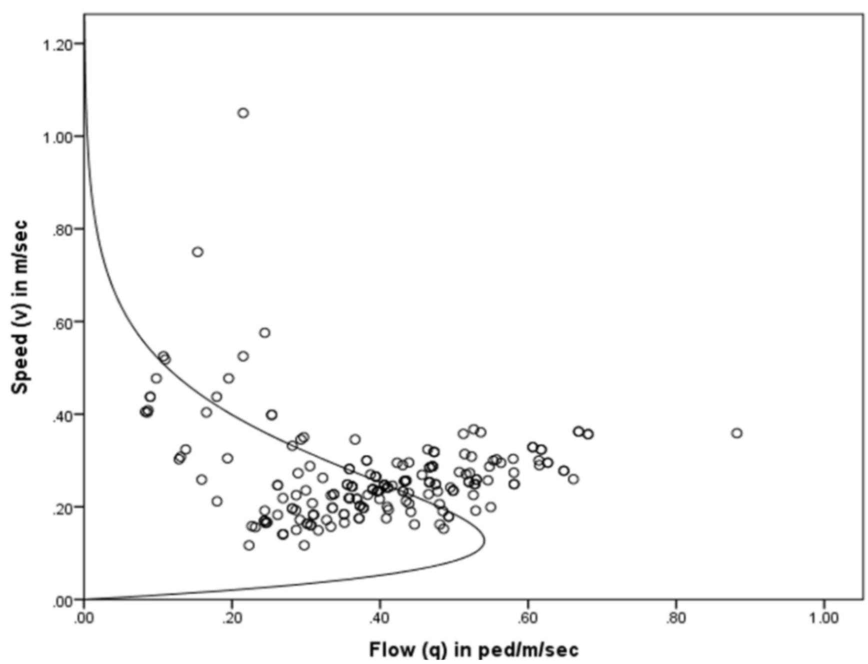

Fig. 12: Speed-flow relationship for downward stairways

The flow-density relationship is parabolic like level walkways and upward stairways, which is presented by Fig. 11. Figure 12 shows an inverse parabolic relationship for speed and pedestrian flow. The best fitted lines are expressed by Eq. (10) and (11), respectively:

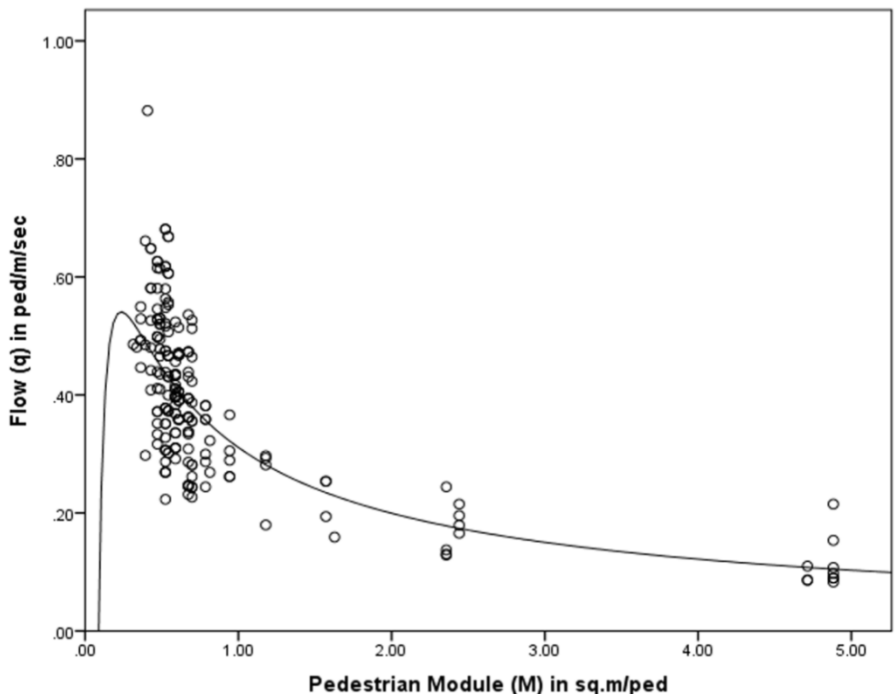

Fig. 13: Flow-pedestrian module relationship for downward stairways

$$q = k(0.311 - 0.127\ln(k)) \quad (10)$$

$$q = v\,e^{(2.449 - 7.874v)} \quad (11)$$

The relationship between pedestrian flow and pedestrian module is presented in Fig. 13. This figure also shows an inverse parabolic relationship like level walkways and upward stairways. Equation (12) gives the best fitted line. The maximum flow on downward stairways is obtained for a pedestrian module of 0.23 m^2/ped:

$$q = \frac{1}{M}\left(0.311 + 0.127\ln(M)\right) \quad (12)$$

CONCLUSION

This study investigates the pedestrian characteristics inside a hall room and for upward and downward stairways. Pedestrians were observed to move faster on level walkways than on stairways. On level walkways, the way of pedestrian is not as fixed as the stairways and the walking of pedestrian is also not controlled in some situations, so pedestrians can change their walking speed randomly to avoid interactions with other pedestrians. But on stairways, the speed of pedestrian is affected greatly by the speed of the front pedestrian. Usually they cannot overtake the front pedestrian. Also, pedestrians need to overcome gravity in upward movement and control it carefully in downward movement. Comparing with the findings of previous studies, this study shows that the pedestrian flow characteristics for indoor and outdoor facilities are not the same. In addition, the walking speed during egress from a hall room is higher compared to other indoor facilities such as railway station. Different speed-density-flow models were developed for each observation site. As pedestrian flow characteristics vary based on the type of facility, the findings in this study could be set as a basis for the development of evacuation models for hall room type facilities.

The same color of convocation gowns and hats of the graduates inside the hall room made it difficult to identify them during data extraction from the recorded video file. Only pedestrians that could be identified throughout their travel along the test stretch were considered for data extraction. Thus, there is some selection biasness that exists in the collected data set, which is one of the limitations of this study. In addition, inside the hall room movements of the graduates were more systematic, which actually did not reflect an emergency situation. During an emergency condition, pedestrian movement may be different. This is also another limitation of this study. In future study, to overcome this drawback, based on pedestrian characteristics in normal condition, a simulation study could be done to generate data and pedestrian flow characteristics for emergency situation.

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